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A study of pre-equilibrium fraction in (n,p) reactions between 10–20 MeV

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Abstract : Excitation functions for several (n,p) reactions [^{27}Al(n,p) ^{27}Mg, ^{48}Ti(n,p) ^{48}Sc, ^{49}Ti(n,p) ^{49}Sc, ^{54}Fe(n,p) ^{54}Mn, ^{56}Fe(n,p) ^{56}Mn, ^{64}Zn(n,p) ^{64}Cu, ^{66}Zn(n,p) ^{66}Cu, ^{76}As(n,p) ^{76}Ge, ^{109}Ag(n,p) ^{109}Pb and ^{197}Au(n,p) ^{197}Pt] have been calculated using exciton model of Griffin in combination with statistical Hauser Feshbach model in the energy range 10–20 MeV. Analysis of data has indicated a considerable amount of pre-equilibrium emission in such reactions. Dependence of pre-equilibrium fraction on excitation energy, target mass number, atomic number, neutron number and asymmetry parameter has also been studied

Keywords : Nuclear reaction, pre-equilibrium emission, model calculation

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1. Introduction

Reaction mechanism at moderate excitation energies is still not well established. There are indications of both equilibrium as well as pre-equilibrium emission in such reactions. At relatively lower excitation energies, the observed features of neutron induced reactions are in reasonable agreement with the theories for compound nucleus formation followed by statistical particle evaporation. At relatively higher energies, the reaction proceeds through the direct interactions. However, at moderate excitations it is quite possible that the nuclear particles are ejected after the first projectile target interaction but prior to the statistical equilibrium characteristic of the compound nucleus reaction [1]. The process of interaction may be considered to pass through a cascade of nucleon-nucleon interactions. Each stage of the interaction may be characterised by the particle hole (*ph*) pair together called excitons. The particles which are emitted before the establishment of statistical equilibrium of the compound system are called pre-equilibrium (PE) particles or sometimes referred to as the pre-compound particles. The probability of emission of PE-particles is expected to decrease

from a stage to the next on account of the available energy getting distributed throughout the compound system with the lapse of time, resulting ultimately in the statistical equilibrium. As such, the study of excitation functions may give useful information about the reaction mechanism.

The pre-equilibrium fraction FR is a measure of relative strength of pre-equilibrium component needed to reproduce the excitation functions and reflect the relative importance of equilibrium and pre-equilibrium processes. The analysis of excitation functions allows one to deduce the pre-equilibrium fraction as a function of incident projectile energy. The calculations of the excitation functions have been performed using an admixture of equilibrium and PE emissions. Brief details of these calculations are presented in Section 2, while the results and discussion are given in Section 3 of this paper.

2. Calculations

The theoretical calculations have been performed using the statistical models. The CN calculations have been performed using the Hauser-Feshbach model [2] while the exciton model of Griffin [3] has been used for simulating the PE contributions. The details of these calculations are described elsewhere [4]. A computer code ACT [5] developed on the lines of code STAPRE [6], has been used for these calculations. The computer code ACT [5] takes sequential evaporation of particles and considers pre-equilibrium emission in the first step of de-excitation of the compound system where the excitation energy is sufficiently large. The pre-compound and compound nucleus models used to calculate the cross sections for (n,p) reactions in this work have been chosen to meet the following criteria :

(i) Both the models should be set free of adjustable parameters as much as possible.

(ii) All input parameters common to the two models are to be determined in advance and used in a unified way.

In Table 1, the sources of values of all input parameters appearing in the compound nucleus and pre-compound models are listed. In the pre-compound calculations, two parameters are required : (1) The average squared matrix element $|\overline{M}|^2$ for two body residual interactions and (2) the initial exciton number n_0. The values of all common input parameters for both compound and pre-compound calculations have been kept same throughout these calculations. Since the value of average square matrix element $|\overline{M}|^2$ is required to reproduce the experimental data, depends sensitively on details of the employed model. However, no reliable microscopic calculations exist for the two-body interaction in the nucleus. The expression of $|\overline{M}|^2 = kA^{-3} E^{-1}$ [7] nevertheless, leaves us with K as a free parameter. With the view of fixing the free parameter K, the excitation functions for all the reactions studied have been calculated using different values of K (*i.e.* 430, 700, 1700 and 3500 MeV^3) keeping the other input parameters constant.

From these calculations, it is observed that for K = 430 MeV^3 the maxima of the calculated excitation functions, which generally occurs around 14 MeV in the experimental data, shifts towards the higher energy side and the calculated excitation functions lie above

the experimental data, while for K = 1700 MeV^3, the maxima of the calculated excitation functions shifts towards the lower energy side and over all excitation functions lie below

Table 1. Input parameters in the evaporation and exciton models in (n,p) reactions.

Input parameter	Input parameter sources	
	Compound nucleus evaporation model	Precompound exciton model
1. Separation energies S_α (β)	Wapstra and Bos Tables [11]	Wapstra and Bos Tables [11]
2. The level density parameter 'a'	Huang and He-Ping [12]	—
3 Single particle level density $g = \frac{6}{\pi^2} a$	—	Gilbert and Cameron [13]
4 Pairing (δ)	Gilbert and Cameron [13]	—
5. Decay scheme of nuclei	Lederer and Shirley Tables [14]	Lederer and Shirley Tables [14]
6. The transmission coefficients	Blann-Vonach optical potential [15]	Blann-Vonach optical potential [15]
7. Initial exciton number n_0	—	$n_0 = 3$
8 Parameter K ($\lvert\overline{M}\rvert^2 = KE^{-1}A^{-3}$)	—	Free parameter

the experimental data. In our calculations, the best fit reproduction of the position of the maxima as well as the total excitation function has been obtained with K = 700 MeV^3.

Such an analysis was also performed by Kalbach [8], who determined the value of $\lvert\overline{M}\rvert^2$ using K = 400 MeV^3. Although the above two results are obtained from analysing nucleon induced reactions in different energy ranges and some aspects of the analysis are different (competition of pre-compound and evaporation processes *vs* competition of pre-compound and direct processes [8]). The difference in the values of the K obtained in this work and in [8] remains difficult to explain. The K value obtained in present work agree very well with the overall best-fit value K = 700 MeV^3 obtained in [9]. An analysis of (n,p) reactions performed by Fu [10] also yields K = 700 MeV^3.

In order to see the effect of variation in the values of initial exciton, number n_0 on calculated excitation functions, calculations for different initial exciton configurations n_0 = 3, 5 and 7 have been performed. The results of these calculations show that, most of the pre-equilibrium protons are emitted from the initial exciton states : 85–90% from n_0 = 3, 8–14% from n_0 = 5 and < 2% from n_0 = 7. It reflects from these calculations that lower value of initial exciton number gives, larger pre-compound contributions. It is because of the fact that lower value of n_0 means larger number of two-body interactions prior to the establishment of equilibrium characteristic of the compound nucleus resulting in larger pre-

compound contributions. This value of $n_0 = 3$ $(2p+1h)$ may also be justified since the first interaction may give rise to the excitation of one particle above Fermi level leaving behind a hole in the excited state. To have a quantitative estimate of the contribution of pre-equilibrium emission to the total cross section for (n,p) reactions between 10–20 MeV, the fraction of pre-equilibrium emission FR has been calculated from the expression :

$$\frac{d\sigma}{dE}(n,p) = [1-FR]\,\frac{d\sigma_{CN}}{dE}(n,p) + \frac{d\sigma_{PE}}{dE}(n,p), \tag{1}$$

where, the terms used have their usual meaning.

3. Results and discussion

The excitation functions for the reactions $^{27}Al(n,p)^{27}Mg$, $^{48}Ti(n,p)^{48}Sc$, $^{49}Ti(n,p)^{49}Sc$, $^{54}Fe(n,p)^{54}Mn$, $^{56}Fe(n,p)^{56}Mn$, $^{64}Zn(n,p)^{64}Cu$, $^{66}Zn(n,p)^{66}Cu$, $^{76}As(n,p)^{76}Ge$, $^{109}Ag(n,p)^{109}Pd$ and $^{197}Au(n,p)^{197}Pt$ have been calculated in the energy range 10–20 MeV and are shown in Figure 1. The pre-equilibrium fraction FRs have also been calculated for all these reactions. In the present calculations, FR is inherently energy dependent, which is

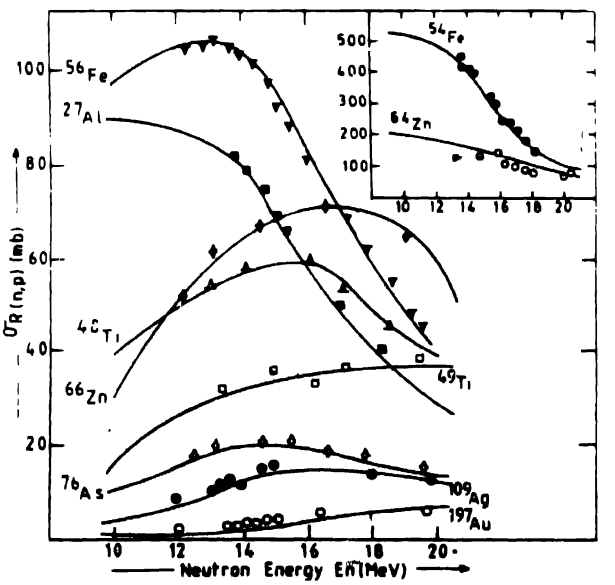

Figure 1. Excitation functions for all the target nuclei presently studied.

derived from the consideration of internal transition rates and continuum decay rates. The FR is taken to be proportional to the cumulative sum of the probability of finding any particle in the continuum for every possible configuration during the process of equilibration. We define the pre-equilibrium fraction as

$$FR(E) = \frac{\sigma_{PE}(n,p:E)}{\sigma_R(n,p:E)}. \tag{2}$$

Here $\sigma_{PE}(n,p : E)$ and $\sigma_R(n,p : E)$ are the pre-compound and total reaction cross sections at a given excitation energy E, respectively.

In the present analysis, a considerable amount of pre-equilibrium contribution has been found in (n,p) reactions. The calculated FRs are shown in Figure 2. It may be seen from this figure that the pre-equilibrium fraction FR increases almost linearly with the increase in neutron energy. Also it may be inferred that FRs trend to reach some saturation

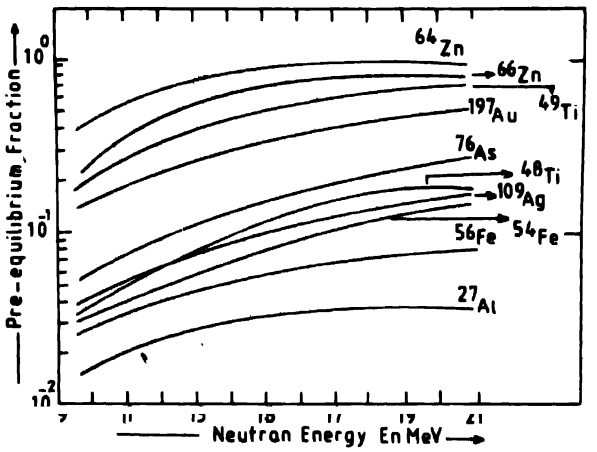

Figure 2. Variation of pre-equilibrium fraction FR as a function of neutron energy, En.

values for every target but at different incident energies. It may also be observed from this figure that FR varies for different target nucleus. It may also be inferred that the pre-equilibrium processes make substantial and in some cases dominant contribution to the reactions initiated by neutrons from 10 to 20 MeV. In middle weight nuclei like ^{49}Ti, ^{64}Zn and ^{66}Zn the contribution of FR is about 50% or more in the higher energy region while in other cases, its contribution is 4–30%. In case of ^{197}Au (heavy nuclei), the reaction proceeds predominantly by the pre-compound emission, and the evaporation component is negligibly small. It may be observed that there is no regular variation of FR with the atomic mass number A of the target nucleus. It is because, FR depends on many parameters (*i.e.* exciton number n_0, the strength factor of the two-body residual interactions K *etc.*) in a complicated way. The FRs at a fixed incident energy of 20 MeV for all the target nuclei presently studied, have also been calculated and plotted against atomic mass number A, atomic number Z, neutron number N and asymmetry parameter $\frac{(N-Z)}{A}$ of the target nucleus in Figures 3(a) and 3(b). It may be observed from these figures that there is no regular dependence of FR on these parameters also.

In literature, no definite trends for the variation of FR with changes in initial exciton number n_0, excitation energy or compound system mass number has been reported. It is however reasonable to assume that the pre-equilibrium fraction depends on the excitation

energy of the compound nucleus. The FR is plotted against excitation energy E in Figure 4. The FR increases with the increase in excitation energy in a typical way and tends to reach

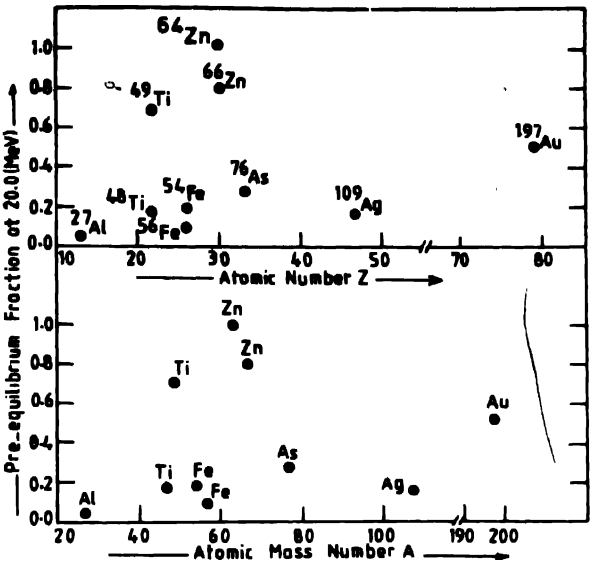

Figure 3(a). Variation of pre-equilibrium fraction, FR with atomic mass number A and atomic number Z of the target nucleus at 20.0 MeV

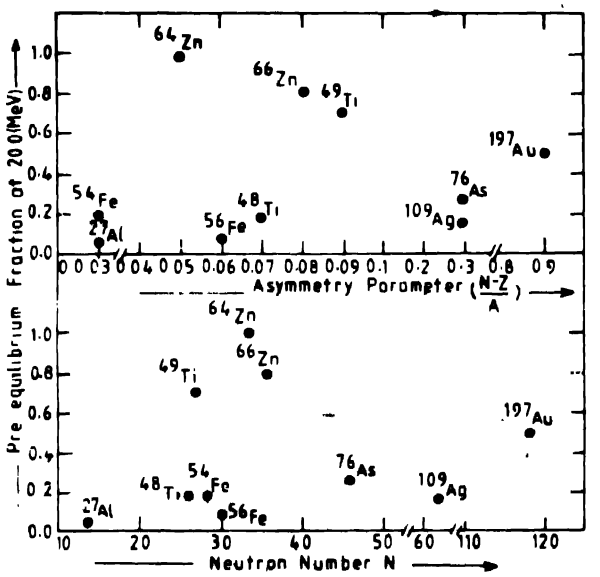

Figure 3(b). Variation of pre-equilibrium fraction, FR with neutron number N and asymmetry parameter $\frac{(N-Z)}{A}$ of the target nucleus at 20.0 MeV.

towards a saturation value. In case of Ti, Fe and Zn where two isotopes of each are studied, threshold excitation energy for pre-equilibrium emission is different for different isotopes.

being lower for the isotope of higher mass number. This may be due to the lower value of Coulomb barrier for the systems of higher mass number as compared to the systems of lower mass number. In case of ^{54,56}Fe and ^{64,66}Zn, the over all FRs decrease with the asymmetry parameter. On the other hand, for ^{48,49}Ti reverse is the case.

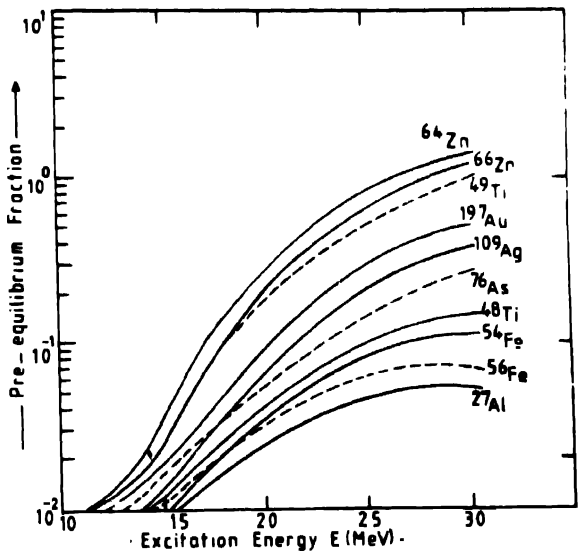

Figure 4. Variation of pre-equilibrium fraction, FR as a function of excitation energy E, of the compound system.

The overall FR trend for ^{49}Ti lie above the FR trend for ^{48}Ti. Since the excitation energy may not be equally distributed among all the nucleons of the compound system, only a few and not all the nucleons take part in pre-equilibrium emission process. In the first few steps of de-excitation, the excitation energy in excess of Coulomb barrier (E–$E_{C.B.}$) gets distributed among the surface nucleons of the compound system. Lower value of the Coulomb barrier for the systems of higher mass number reduces the probability of the proton emission for heavy isotope. So the overall FR decreases with increase in asymmetry parameter for Fe and Zn isotopes. In case of Ti isotopes, since the reaction Q value for ^{49}Ti is higher than that of ^{48}Ti, the decrease of Coulomb barries with increase in asymmetry parameter is more than compensated by increasing reaction Q value. As a net result probability of proton emission for heavy isotopes of Ti increases and the overall FR trend for ^{49}Ti lie above the trend for ^{48}Ti.

4. Conclusions

From the present analysis, it may be concluded that the pre-equilibrium processes play an important role in the reactions initiated by the neutrons of 10–20 MeV energy. The values of initial exciton number $n_0 = 3$ (2 particles + 1 hole) and the parameter $K = 700$ MeV^3 have been found to give best fit to the data. The PE fraction increases with increase in energy for all the nuclei studied presently. Though, the present data on FR are limited yet they cover

relatively wide mass range from 27 to 197. However, it requires further investigations to complete the systematic study and confirmation of the trends.

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